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# VIII.—*Experimental Researches on the Lifting Power of the Electro-Magnet.* Part III.

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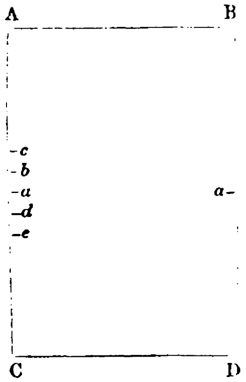
Read November 30, 1857.

In my last paper on this subject I showed that with a given exciting power, measured by $\psi$ = product of the current into the number of spires, the lifting force of an electro-magnet is less as the spires are distributed over a greater length of its arms. Thus, it is seen from Tables XII. and XIII., that, with the same $\psi$, the forces are 911 and 733, the lengths covered being $2^{i}\cdot 1$ and $10^{i}\cdot 1$ for each arm. I showed that part of this diminution arises from the oblique action of the remote spires, and part from the imperfect transmission of the magnetism in their immediate vicinity. These, however, account for but a small portion of it, as is evident if the spires be kept in a given position while the length is varied.

It is the object of this paper to detail a series of such experiments, which were instituted in hopes of finding some simple relation between the position of the spires, the length of the magnetic circuit, and the lifting force $L$ : and though I have been disappointed in this, yet I think the results are not without value, both as pointing out some of the influences which complicate the problem, and as affording numerical data by which theoretical investigations on this subject may be tested.

Before describing them, it may be useful to state what appears to be the action occurring in an electro-magnet, which is excited while its poles are connected. As far as I know, this case has not been examined by theory, and is quite different from that of a permanent magnet, whose poles are unconnected. There, free magnetism, which is null at the centre, increases with opposite polarities towards the extremities : there is scarcely any free magnetism, and the internal molecular excitation must be of quite a different character. The state of things is probably of this sort.

Let ABCD represent the magnet, supposed continuous ; let it be excited by a circular current at $a$. The action of this on the differential slice lying in its plane will induce opposite polarities on its surfaces, till their natural attraction, aided by the coercive force of the molecules, balances that action. But these polarities induce opposite ones on the adjacent surfaces of the slices $b$ and $d$,—less, however, in intensity; both because *their* coercive force resists the inducing force, and because it is weakened by the intermolecular space. These, again, induce on $c$ and $e$, which are also affected by $a$, though more weakly ; and so on through the whole circuit. These induced polarities react on $a$ itself : its + no longer tends to its – with the same force, for it is drawn the other way by the combined effects of the – ones $b$, $c$, &c. Therefore, the current is able to produce a higher polarization of $a$ than if it were alone, which again acts more powerfully on its neighbours ; so that a far greater development of magnetic force is obtained, than would be possible if the magnetic circuit were interrupted, and the magnet were a mere bar covered with spires.($a$)



When the equilibrium of these forces is obtained, it is evident that the molecular polarity must be greatest at $a$, and decrease symmetrically on each side, till it becomes a minimum at $a$, the opposite point of the circuit. The magnitude of the maximum is independent of the place of $a$, but must be a function of $c$, the length of the circuit, such that it decreases as $c$ increases, but will continue finite when that is infinite. At any other point $b$ the polarization depends on the maximum, conjointly with the distance $ab$, and also with $c$.($b$)

If instead of one circular current a spiral or helix be used, the action is the same, though the distribution of the magnetism is somewhat altered.

At any section A the magnetism will be the resultant of the force transmitted by induction through the branch $\mathrm{A}a = z$, and that through the complementary branch $a\mathrm{CDBA} = c - z$.

If a second spiral or helix be placed symmetrical to the first at $a$, the effect at A is the resultant of four components, the two first named, and the inductions of the branch $a\mathrm{BA} = z + k$, and of $a\mathrm{DCA} = c - k - z$. The same principle applies to any additional spires, and if they be symmetrically placed on the branches AC and BD, the forces developed at A and B are equal.(*c*)

If the forces excited by each spire were transmitted undiminished by induction, and if they were compounded by mere addition, it would be an easy matter to compute the force at either of these points; but it will subsequently be shown that these resultants are always less than the sum of the components, and that the law of their composition, as well as that of the transmission by induction, are yet unknown.(*d*)

Now let the magnet be discontinuous at A and B: AB becomes a keeper; but this makes no change, except as far as the separations there make the inductive propagation through the circuit more difficult. However closely the surfaces of contact may be fitted, and though they are pressed together very powerfully by the attraction of the magnet, it is certain that they are separated by an interval far greater than the distance between the molecules of iron; it is even possible that this interval may be sufficient to change the law of inductive propagation.(*e*)

The following experiments will illustrate the statements (*a*) and (*c*):—

The part CD of the magnet (described in my second paper, vol. xxii., page 508) is a moveable slide, which can be set to give AC any value from 0 to $11^{\mathrm{i}}$. If it be removed, and both arms be excited, the force at A is only the resultant of the inductions through $z$ and $z + k$, themselves diminished by the interruption of the circuit. If, also, for AB be substituted a block of brass, to which cylinders of iron are fixed $2^{\mathrm{i}}$ high, and of the same diameter (that of the magnet), then, with the slide in its place, we have the resultant of induction through ($z$), and that through ($c - k - z$); if it be removed, there is left only ($z$). The helices used are described in No. 11, page 519, and $\mathrm{AB} = k$ is 6 inches.

The temperature is given to show that no sensible portion of the differences is due to a variation of it; but in these, as in most of the other results given in this paper, no temperature correction is made, as it must be specially investigated for each altered arrangement of the magnet.

TABLE XV.

| No. | Helices. | *c.* | *z.* | *T.* | $\psi$. | *L.* | Ratio. | State of Magnet. | Observations. |
|---|---|---|---|---|---|---|---|---|---|
| 66 | G, . . . . | 28·2 | 3·8 | 64°·9 | 547·99 | 750·07 | 1·000 | Normal, . . . . . | 5 |
| 67 |  | 28·2 | 3·8 | 65°·6 | 547·99 | 21·77 | 0·029 | Brass keeper, . . . . | 5 |
| 68 | F at keeper, . | 32·2 | 1·0 | 70°·8 | 546·75 | 784·73 | 1·000 | Normal, . . . . . | 5 |
| 69 |  | 32·2 | 1·0 | 71°·8 | 547·90 | 119·52 | 0·183 | Slide removed, . . . | 5 |
| 70 |  | 32·2 | 1·0 | 71°·5 | 549·73 | 20·67 | 0·026 | Brass keeper, . . . . | 5 |
| 71 | F at slide, . . | 32·2 | 9·0 | 64°·1 | 549·07 | 658·81 | 1·000 | Normal, . . . . . | 17 |
| 72 |  | 32·2 | 9·0 | 72°·1 | 549·70 | 11·96 | 0·018 | Slide removed, . . . | 5 |
| 73 | B at keeper, . | 32·2 | 1·0<br>9·0 | 68°·6 | 544·30 | 766·53 | 1·000 | Normal, . . . . . | 5 |
| 74 | J at slide, . . | 32·2 | 1·0<br>9·0 | 69°·8 | 544·30 | 82·84 | 0·108 | Slide removed, . . . | 5 |
| 75 | F, B, J, K, L covering the arms, . . | 32·2 | 5·0 | 73°·1 | 2005·72 | 1001·49 | 1·000 | Normal, . . . . . | 12 |
| 76 |  | 32·2 | 5·0 | 70°·3 | 1997·47 | 698·25 | 0·698 | Slide removed, . . . | 12 |
| 77 |  | 32·2 | 5·0 | 74°·0 | 1884·00 | 85·05 | 0·085 | Brass keeper, . . . . | 5 |
| 78 |  | 32·2 | 5·0 | 76°·2 | 2016·09 | 35·34 | 0·035 | Ditto, and slide removed, | 5 |

The great loss of magnetic force arising from the removal of either of the connexions AB, CD (the former in particular) is remarkable. This case occurs in 67, 70, and 77, and is equivalent to that of a bar magnet whose length is $c-k$ lifting by one of its poles. Even in 77, where the effect is greatest, it is not 0·09 of the full power of the magnet, and this proves that the excitation of the molecules must be greatly diminished. It will hereafter be shown that in, for instance, 68, the induction through the keeper from B to A is nearly three-fourths of the direct effect of the helix at A; therefore, supposing that the resultant were even the sum of its components, the cutting off this induction should still leave four-sevenths of that resultant, instead of 0·03. It seems, therefore, that the brass keeper reduces the excitation fully 29 times. In 78 the action is that of a magnet of half the length of 77, or $\frac{1}{2}c-k$, and is proportionally less. The greater loss caused by removing AB, than by CD, is easily explained from what is stated in (*c*). In the first case, the induction from the second arm takes place through the distance $c-z-k$, in the other, through the lesser one $z+k$. The high ratio in 76 is also to be anticipated: in 68, $\psi=549$ is applied to two inches of the arm at B, the effect of which is induced through $z+k=7^{i}$ at A; in 76, one $\psi=400$ acts through the same space, but in addition another helix acts on the next 2 inches of the arm with equal energy, and at the inducing distance $9^i$, and so on through the five. A similar addition is made to the inducing forces of the arm AC, so that the effect may easily be four times what it is in the other case. I may remark that the removal of the slide, especially when the arms are of considerable length, gives an approximation to the case of $c$ infinite, and that though an increase of the number of spires and the quantity of current will augment the effect greatly, yet it is not probable that any finite amount of them will equal the influence of closing the circuit.

That the force $L$ is composed as stated in ($c$), may be shown by measuring it in different positions of the slide CD, while the helices are kept in a given position. In this case the components $(z)$, $(z + k)$, with a given $\psi$, should be invariable, and any differences which are found can only depend on the other two. In general, two positions were chosen for each value of $c$, one in contact with the keeper, the other with the slide. In this last case the forces excited at C and D are the same which in the other are measured at A and B, and as in both $c$ is the same, the change depends on $z$ only. I therefore hoped that by comparing the series $L_k$ I might ascertain the effect of the circuit, and, if successful in that, comparing each $L_s$ with its own $L_k$, I might get the law of $(z)$. The first sets were made with the spirals A, with $\psi$ nearly 124·69, and reduced exactly to it by interpolation from Table VIII.

TABLE XVI.

| No. | *h.* | *z.* | *c.* | *L.* | *T.* | *μ.* | Ratio. | Position. | Observations. |
|---|---|---|---|---|---|---|---|---|---|
| 79 | 0·15 | 0·07 | 12·3 | 495·95 | 65°·6 | 1·0000 | 1·0000 | Keeper, . . | 18 |
| 80 | 2·1 | 0·07 | 16·2 | 458·88 | 64°·3 | 0·8767 | 0·9252 | Keeper, . . | 17 |
| 81 | 2·1 | 2·07 | 16·2 | 436·35 | 64°·2 | 0·8122 | 0·8798 | Slide, . . | 22 |
| 82 | 4·1 | 0·07 | 20·2 | 407·82 | 63°·5 | 0·7428 | 0·8223 | Keeper, . . | 35 |
| 83 | 4·1 | 4·07 | 20·2 | 384·03 | 64°·2 | 0·7051 | 0·7744 | Slide, . . | 35 |
| 84 | 6·1 | 0·07 | 24·2 | 342·72 | 62°·5 | 0·6307 | 0·6910 | Keeper, . . | 17 |
| 85 | 6·1 | 6·07 | 24·2 | 319·04 | 64°·0 | 0·6073 | 0·6433 | Slide, . . | 22 |
| 86 | 8·1 | 0·07 | 28·2 | 295·24 | 64°·6 | 0·5531 | 0·5953 | Keeper, . . | 17 |
| 87 | 8·1 | 8·07 | 28·2 | 269·88 | 64°·4 | 0·5149 | 0·5442 | Slide, . . | 22 |
| 88 | 10·1 | 0·07 | 32·2 | 254·89 | 64°·9 | 0·4949 | 0·5139 | Keeper, . . | 40 |
| 89 | 10·1 | 2·07 | 32·2 | 246·28 | 66°·1 | 0·4821 | 0·4977 | $2^i$ from $k$, . | 12 |
| 90 | 10·1 | 4·07 | 32·2 | 232·52 | 68°·8 | 0·4612 | 0·4699 | $4^i$ from $k$, . | 12 |
| 91 | 10·1 | 6·07 | 32·2 | 228·55 | 66°·2 | 0·4572 | 0·4619 | $6^i$ from $k$, . | 12 |
| 92 | 10·1 | 8·07 | 32·2 | 224·57 | 66°·9 | 0·4509 | 0·4538 | $8^i$ from $k$, . | 12 |
| 93 | 10·1 | 10·07 | 32·2 | 223·50 | 64°·8 | 0·4480 | 0·4506 | Slide, . . | 29 |

The second column gives $h$, the distance between the slide and keeper; $\mu$ is, as formerly, the ratio of the actual $\psi$ to that which would produce the same $L$, if the circuit were a minimum.[*] The next column gives the ratio of the $L$ in this last case to each of the others. In 89–92 the spirals were placed in intermediate positions. These were the result of a separate set; but the values for $z = 0{\cdot}07$, and $z = 10{\cdot}07$, agree so closely with the first set that it seemed best to group them together.

It is seen at once that the value of $L$ decreases as the length of the circuit is increased: thus, for $c = 32{\cdot}2$, it is only half what it is when $c = 12{\cdot}3$. The effect of $z$ is similar, though less in amount, and is also dependent on $c$. These relations are exhibited in—

### Table XVII.

| $h$. | Ratio of $L_k$. | Ratio of $L_s$. | $\frac{L_s}{L_k}$. | $c = 32{\cdot}2$<br>$z =$ | $\frac{L_z}{L_0}$. |
|---|---|---|---|---|---|
| 2·1 | 0·9252 | 0·8798 | 0·9509 | 2·07 | 0·9662 |
| 4·1 | 0·8223 | 0·7744 | 0·9416 | 4·07 | 0·9122 |
| 6·1 | 0·6910 | 0·6433 | 0·9309 | 6·07 | 0·8967 |
| 8·1 | 0·5953 | 0·5442 | 0·9142 | 8·07 | 0·8811 |
| 10·1 | 0·5139 | 0·4506 | 0·8768 | 10·07 | 0·8768 |

The second column gives the ratio of $L$, when the circuit is a minimum, to that obtained with other circuits, the spirals being at the keeper; the least complicated case, as depending only on $c$, and giving the maximum of effect for a given circuit.[†] The third column gives the ratio of the same $L$ to that got when the spirals are on the slide. This involves both $z$ and $c$, and gives the minimum effect; but as the influence of the former is not very great, it seems to follow nearly the same march. The fourth column gives, for each pair, the ratio of the effect with the spirals at keeper, to that with them at slide. This ratio decreases much more slowly than either of the preceding; for instance, a change of $c$ from 16·2 to 32·2 changes the ratio of $L_k$ from 0·93 to 0·51; but the same change of $c$, combined with that of $z$ from 0·07 to 10·07, only alters this from 0·95 to 0·88. The comparatively small influence of $z$ is still more plainly shown by the sixth column, which gives for $c = 32·2$ the ratios of the maximum to the $L$ obtained with the $z$ in the fifth column by Nos. 88–93.

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[*] Of these $\mu$ appears best for comparing the powers of helices, but the other is preferable for a comparison of the magnets. In the range of these experiments they agree sufficiently for all purposes of interpolation; but the former becomes very irregular when the maximum is approached, as will be obvious when the progression of $L$ is examined. I think it likely that the quotient of the other by the area of the magnet's section is the best measure of the efficiency of that particular form of magnet.

[†] The maximum would, I think, be obtained if the spirals could be placed at the middle of the keeper AB, and the minimum at the middle of the base CD.

A similar series made with the helices $F . F'$, and with $\psi = 549·08$, is given in—

TABLE XVIII.

| No. | $h$. | $z$. | $c$. | $L$. | $T$. | $\mu$. | Ratio of $L$. | Position of Helices. | Observations. |
|---|---|---|---|---|---|---|---|---|---|
| 94 | 2·1 | 1·0 | 16·2 | 867·54 | 71°·4 | 0·6714 | 1·0000 | Keeper, . . . | 10 |
| 95 | 4·1 | 1·0 | 20·2 | 833·31 | 74°·3 | 0·6144 | 0·9605 | Keeper, . . . | 10 |
| 96 | 4·1 | 3·0 | 20·2 | 805·05 | 64°·8 | 0·5629 | 0·9280 | Slide, . . . . | 18 |
| 97 | 6·1 | 1·0 | 24·2 | 812·74 | 73°·6 | 0·5768 | 0·9369 | Keeper, . . . | 10 |
| 98 | 6·1 | 5·0 | 24·2 | 761·53 | 64°·2 | 0·4861 | 0·8778 | Slide, . . . . | 17 |
| 99 | 8·1 | 1·0 | 28·2 | 801·72 | 73°·7 | 0·5570 | 0·9241 | Keeper, . . . | 15 |
| 100 | 8·1 | 7·0 | 28·2 | 718·78 | 65°·5 | 0·4098 | 0·8266 | Slide, . . . . | 17 |
| 101 | 10·1 | 1·0 | 32·2 | 781·73 | 71°·7 | 0·5214 | 0·9011 | Keeper, . . . | 10 |
| 102 | 10·1 | 9·0 | 32·2 | 658·81 | 64°·1 | 0·3342 | 0·7594 | Slide, . . . . | 17 |
| 103 | 10·1 | 1·0<br>9·0 | 32·2 | 718·56 | 61°·0 | 0·4095 | 0·8283 | F at keeper, F′ at slide, . . | 12 |

The ratios, given as before, are as follows:—

TABLE XIX.

| $h$. | Ratio of $L_k$ | Ratio of $L_s$. | $\frac{L_s}{L_k}$. | Ratio of $L_k$ for $A . A'$. | Ratio of $L_s$ for $A . A'$. |
|---|---|---|---|---|---|
| 4·1 | 0·9605 | 0·9280 | 0·9661 | 0·8887 | 0·8801 |
| 6·1 | 0·9369 | 0·8778 | 0·9370 | 0·7469 | 0·7312 |
| 8·1 | 0·9241 | 0·8266 | 0·8945 | 0·6434 | 0·6185 |
| 10·1 | 0·9011 | 0·7594 | 0·8427 | 0·5555 | 0·5122 |

There is the same decrease of $L$, as $c$ and $z$ increase ; but it is much slower, as is especially seen by comparing the two first sets of ratios with the fifth and sixth columns, which give the ratios of $L_k$ and $L_s$ obtained with the spirals for $h=2{\cdot}1$, with their other values. This fact arises apparently from the more powerful action of the spiral in its plane, being neutralized by its feeble action out of that plane, and from the greater distance through which it must act by induction. But in any case it is obvious, that the lifting power of an electro-magnet is increased by making the length of the circuit as short as possible, and by bringing the wire of the helices, or spirals, as near the poles as is compatible with having the necessary number of spires, as was stated in my second paper, p. 522. It will be shown, however, that another plan of arrangement should be adopted when the magnet is intended to act at a distance.

I have tried in vain to find any simple law connecting $L$ with $c$ and $z$, and it probably is not to be found by mere experiment, for—

1. The direct action of a spire on that section of the magnet which is in its plane, can be computed by my equation (4) ; and that on any other by equation (10). Each of these actions is transferred to the sections A and B by induction ; but the law of this induction is not known, and it does not seem probable that it will be possible to evolve it from an effect so complex. Yet more, these inductive actions influence the power of the current itself to excite the intermediate sections in a manner which is still undetermined.

2. In these experiments the observed force is, as I have stated in (*d*), the resultant of four components ; and we do not know the law of this composition. Each of them is the result of an induction through a certain length of iron, but we know nothing of their relative magnitudes. We may get a general notion of the composition of magnetic force by forming a table, such as Table XII., and comparing its $L$ and $\psi$. I think it cannot be doubted that if $\psi$ produces $L$, and $\psi'$ $L'$ ; $\psi+\psi'$ will produce the resultant of $L$ and $L'$. That this may be more easily examined, I have reduced the $L$ to those corresponding to an arithmetical series of $\psi$, for this magnet, which is $2^{i}$ diameter with $c=16^{i}{\cdot}2$ ; and have done the same for the hollow magnet described in my first paper, whose external diameter $=2^{i}$, and its $c=36$ ; for a small one, to be described hereafter, of diameter $=1^{i}$, and $c=27^{i}{\cdot}7$ ; and for one $3^{i}$ diameter, and $c=36^{i}{\cdot}0$.

TABLE XX.

| $\psi$. | Short Magnet. | Hollow Magnet. | Small Magnet. | Large Magnet. |
|---|---|---|---|---|
| 1000 | 1085·24 | 571·00 | 230·68 | 1368·61 |
| 900 | 1062·68 | 553·81 | 228·67 | 1302·71 |
| 800 | 1034·06 | 540·33 | 225·03 | 1230·01 |
| 700 | 994·56 | 519·76 | 220·97 | 1151·30 |
| 600 | 940·95 | 496·40 | 212·65 | 1060·51 |
| 500 | 874·52 | 460·63 | 202·64 | 952·85 |
| 400 | 797·99 | 412·45 | 191·83 | 819·46 |
| 300 | 721·04 | 359·23 | 175·12 | 657·11 |
| 200 | 588·26 | 259·20 | 139·83 | |
| 100 | 329·86 | 133·91 | 63·96 | |

In each of these the relation between the resultant and components is different; for instance, $L\,(1000)$ is composed of $2L\,(500)$; now its ratios to one of them are—

$$1·2410; \qquad 1·2396; \qquad 1·1384; \qquad 1·4364.$$

Again, taking $L\,(600)$ as composed of $2L\,(300)$, they are—

$$1·3050; \qquad 1·3818; \qquad 1·2143; \qquad 1·6139.$$

It will also be observed that when the components are unequal, the smaller one adds but little to the resultant: thus (100) adds but 22·56 to (900); (200) adds 51·18 to (800), in the first magnet,—not a tenth of what they would produce alone. If the ratio of the $L$ in the second column to the others which have the same $\psi$ be taken, it is found to vary but little in the hollow and small magnet, except in $\psi = 100$, where the excitation seems scarcely sufficient to bring the iron into full action; in the first it decreases, in the other increases, as $\psi$ diminishes. For the large magnet it decreases more rapidly, being 1·2611 for $\psi = 1000$, 0·9113 for $\psi = 300$. Probably in all these the central portion of the magnet has not been excited.

3. I thought the complexity of this investigation might be diminished by using a single spiral or helix, and thus having only to deal with the inductions $(z)$ and $(c - z)$. In the ordinary course of my experiments, with each arm equally excited, the force at each polar surface is equal, and as the keeper is

raised by a force $L$, applied at its middle point at right angles to the plane of these surfaces, we have

$$L = 2M;$$

$M$ being the force at each surface. If, however, one arm only be excited, the polar forces are unequal; the weaker gives way first, and the keeper rises, turning round the outer edge of the excited arm. In this case we have, calling $r$ the radius of the arm,

$$2M' = L' - \frac{r}{\frac{1}{2}k + r} \times (M - M').$$

A second equation is obtained by assisting $M'$ with a downward pressure $P$, applied exactly in the axis of the unexcited arm, and sufficient to make it prevail; then $M$ gives way, and thence

$$2M = L - \frac{r}{\frac{1}{2}k + r} \times (P - M + M'),$$

from which $M$ and $M'$ are found.

In this magnet $r = 1$, $k = 6$, whence

$$2M = L + \frac{L - L'}{6} - \frac{7P}{24};$$

$$2M' = L' - \frac{L - L'}{6} + \frac{P}{24}.$$

To apply the pressure $P$ a lever was used, whose ratio $= 5{\cdot}8$, turning on a centre in a strong vertical bar of iron screwed to the slide; weights of any required amount were hung at its extremity, and it pressed on a rod of steel, pointed at each end, one of which was set in a hole punched in its lower surface, the other in the centre of the screw which is fixed in the keeper, with its head entering the central pole in the magnet to serve as a guide. For each position of the slide one of these rods was provided, so adjusted that the lever was horizontal, and of course the rod exactly vertical. The bar prevented the application of the larger helices to the arm BD, near which it was fixed, so that the force $M$ belongs to A, $M'$ to B.

The first set were taken with the spirals A, A′; $\psi$ is nearly 124·69, and the resulting $M$ and $M'$ are reduced to that by interpolation. Only two are available, for at first I used too small a pressure, which was not discovered till they were reduced. They are

TABLE XXI.

| | *z*. | *c*. | *L* and *L'*. | $\psi$. | *T*. | 2*M* and 2*M'* | $\mu$. | Observations. |
|---|---|---|---|---|---|---|---|---|
| 101 | 0·2 | 12·8 | 544·52 | 123·54 | 65°·4 | 539·86 | 1·1051 | 12 |
| 102 | 0·2 | | 451·22 | 123·58 | 67 ·5 | 442·29 | 0·8422 | 12 |

The weight hung to the lever = 14 lbs.; and the pressure *P* is (including that due to the weight of the lever itself) = 83·40.

From the small value of *z*, the condition of the magnet is nearly that described in (*b*), so that *M* is the maximum, and *M'* the minimum force; and they may represent the resultants of (0) + (12·8), and of (6·4) + (6·4). In the ordinary arrangement with a spiral on each arm, each of them would excite *M* at its own arm, and *M'* at the other; the *L*, therefore, corresponding to $2\psi = 249{\cdot}38$ is the resultant of $2M + 2M'$. By interpolation and Table VIII. it appears that this = 746·91, only 0·763 of 982·15, the sum of the components.

A more complete series was made with the helices F, F'. The results are reduced to 549·08, $W = 24$, and $P = 141{\cdot}20$.

TABLE XXII.

| | *z*. | *c*. | *L* and *L'*. | $\psi$. | *T*. | 2*M* & 2*M'*. | $\mu$. | Observations. |
|---|---|---|---|---|---|---|---|---|
| 103 | 1·0 | 16·2 | 986·05 | 549·21 | 68°·7 | 979·90 | 0·8977 | 18 |
| 104 | 1·0 | 16·2 | 775·66 | 550·14 | 69 ·9 | 755·74 | 0·4687 | 12 |
| 105 | 1·0 | 20·2 | 951·98 | 548·01 | 68 ·9 | 947·13 | 0·8494 | 18 |
| 106 | 1·0 | 20·2 | 738·54 | 548·07 | 69 ·6 | 709·44 | 0·3973 | 12 |
| 107 | 1·0 | 24·2 | 906·12 | 548·72 | 71 ·2 | 897·18 | 0·7314 | 12 |
| 108 | 1·0 | 24·2 | 714·08 | 548·32 | 67 ·0 | 688·30 | 0·3685 | 12 |
| 109 | 1·0 | 28·2 | 886·75 | 549·64 | 68 ·5 | 879·78 | 0·6949 | 12 |
| 110 | 1·0 | 28·2 | 679·69 | 548·32 | 67 ·2 | 651·42 | 0·3267 | 12 |
| 111 | 1·0 | 32·2 | 884·09 | 550·44 | 74 ·8 | 878·03 | 0·6912 | 12 |
| 112 | 1·0 | 32·2 | 660·92 | 553·65 | 69 ·8 | 626·28 | 0·3095 | 12 |
| 113 | 9·0 | 32·2 | 748·54 | 548·63 | 68 ·4 | 724·26 | 0·4178 | 12 |
| 114 | 9·0 | 32·2 | 588·92 | 550·80 | 68 ·4 | 567·10 | 0·2598 | 12 |

Here $M$ is the resultant of $(z)$ and $(c-z)$; $M'$ of $(z+6)$ and $(c-z-6)$. In the first five pairs $z$ and $z+6$ are constant, so that the variation of $M$ and $M'$ is due to that of $c$; but even so, it is impossible to get their relation. The variable $u$ cannot be obtained from $R\,(a+u)$, unless the nature of the function $R$ be known. Still, some information may be derived from them.

The ratio of $M$ to $M'$, and the values of the quantities on which they depend, are given for each pair in—

### Table XXIII.

| | $\frac{M'}{M}$. | $z$. | $c-z$. | $z+6$. | $c-z-6$. | $\frac{M_{16}}{M_c}$. |
|---|---|---|---|---|---|---|
| 103–104 | 0·7712 | 1·0 | 15·2 | 7·0 | 9·2 | 1·0000 |
| 105–106 | 0·7491 | 1·0 | 19·2 | 7·0 | 13·2 | 0·9666 |
| 107–108 | 0·7672 | 1·0 | 23·2 | 7·0 | 17·2 | 0·9156 |
| 109–110 | 0·7404 | 1·0 | 27·2 | 7·0 | 21·2 | 0·8978 |
| 111–112 | 0·7133 | 1·0 | 31·2 | 7·0 | 25·2 | 0·8960 |
| 113–114 | 0·7830 | 9·0 | 23·2 | 15·0 | 17·2 | 0·7591 |

The ratio of $M$ to $M'$, notwithstanding some irregularity in the second and third, decreases slowly in the first five; so slowly as to show that the components of each which depend on the constant terms predominate much over the others. In the sixth, where $z$ and $z+6$ are considerably greater, while the others are lessened, the ratio is increased, though the absolute magnitudes are diminished. As $c-z$ and $c-z-6$, having a common difference, tend to equality by these increases, I should expect that the ratio would ultimately be that due to (1) and (7), unless something beside the mere distance interferes with the induction. The last column, which gives the ratio of the first $M$ to those of the other circuits, shows a more rapid decrease, but though in this case there is only $(c-z)$ variable, the law seems unattainable.

It occurred to me as possible that iron in a state of high excitement may not have the same power of transmitting induction as when less magnetic. If so, when each pole has its own helix, as the $M$ then magnetizes the keeper, the $M'$ of the other pole would be transferred with less power, and so also for the remainder of the circuit. In this case $L$ is the resultant of $2M+2M'$, and this would account for the resultant being less than the sum. As $\psi$ would then = 1098·16, it is easy to compute from Tables XII. and XVIII. the values of *L* corresponding to *M*. But we can also compute the $\psi$s, which under similar circumstances would give a force = *M*, and one = *M′*; the sum of these must produce an *L″*, which must also be the resultant of those components, and therefore should be identical with *L*. The result is given in—

### TABLE XXIV.

| | *L*. | *L″*. | *L – L″*. | *L – 2M*. | $\frac{L}{2M+2M'}$. | $\frac{L}{M}$. |
|---|---|---|---|---|---|---|
| 103–104 | 1079·48 | 1088·24 | - 8·76 | 99·58 | 0‘6219 | 1·1016 |
| 105–106 | 1060·51 | 1062·06 | - 1·55 | 113·38 | 0·6402 | 1·1197 |
| 107–108 | 1044·72 | 1033·46 | +11·26 | 147·54 | 0·6589 | 1·1644 |
| 109–110 | 1036·78 | 1013·92 | +22·86 | 157·40 | 0·6771 | 1·1784 |
| 111–112 | 1018·51 | 1005·83 | +12·68 | 140·48 | 0.6771 | 1·1600 |
| 113–114 | 863·31 | 869·38 | - 6·07 | 139·05 | 0·6685 | 1·1923 |

Considering the complicated nature of the process, $L - L''$ is so small that we may safely infer that magnetic excitement does not interfere with the transmission of induction. The three last columns are given to show the relation between a resultant and its components. The first of them, headed $L - 2M$, shows the actual increase of force produced by the lesser component, which, especially for the higher powers, is less than would be anticipated. The second is the ratio of the sum of components to their resultant; and the third the ratio of the larger component to it; both showing that it decreases relatively as they increase. Of course, either higher or lower on the scale, the actual value of the ratio would recede considerably from these.

4. Lastly, the investigation of these laws is impeded by the interruption of inductive transmission, which arises from the discontinuity at A and B, when the keeper rests on the magnet, as stated in (*c*). This effect is shown by comparing the last two pairs in Table XXII. Supposing the helix placed at A, No. 111 represents the force excited there; No. 113, that at C; No. 114, that at D, which is the minimum; and No. 112, that at B. Now the force at C may be expected to be less than that at B, for it is the resultant of $(9^{\text{i}})$ and$(23^{\text{i}}\cdot 2)$; the other of $(7^{\text{i}})$ and $(25^{\text{i}}\cdot 2)$; for, as is shown by the column $L - 2M$, resultants are nearer the larger of their components than the less. It is, however, found

to be 97·98 greater, and no cause of this is evident except the one assigned. To obtain some idea of the probable effect of it in a more direct way, I introduced two additional joints into the circuit. Two discs of soft iron were procured, $2^{i}$ diameter, and $0^{i}{\cdot}25$ thick, with central apertures equal to those of the magnet. They were marked so that they could be placed always in the same position on the polar surfaces, and were accurately fitted by the scraping process both to them and the keeper. If $L'''$ be determined when they form part of the magnet, and $L$ when they are removed, and the magnet is brought to the same length by lowering the slide 0·25, $\psi$ remaining the same, $L - L'''$ is the loss caused by the second pair of joints. The helices F, F′ were used always on the slide; $\psi$ was as near as possible to 549·08, and reduced to that by interpolation.

Table XXV.

| | *h.* | *c.* | *z.* | *L.* | *T.* | *L'''.* | *T.* | *L − L'''.* | $\frac{L}{L'''}$. | Observations. |
|---|---|---|---|---|---|---|---|---|---|---|
| 115 | 2·1 | 16·2 | 1·0 | 886·82 | 63°·6 | 809·08 | 63°·1 | 77·74 | 1·0961 | 12·12 |
| 116 | 4·1 | 20·2 | 3·0 | 798·45 | 61 ·7 | 745·30 | 61 ·0 | 53·15 | 1·0713 | 12·12 |
| 117 | 10·1 | 32·2 | 9·0 | 641·98 | 60 ·6 | 608·51 | 60 ·7 | 33·47 | 1·0550 | 12·12 |

The difference is considerable, and both it and the change of ratio are nearly inversely as $c$. I regret that it did not occur to me to experiment with different values of $\psi$ in order to ascertain whether this effect changes with pressure, but it probably does, and therefore the effect of a single pair of joints will be still greater, and, as such, too considerable to be neglected in any attempt to discover the law of induction in this way. If the supposition in ($c$) be correct, such an interruption in the circuit may be considered equivalent to an increased length of $c$, and half as much of $z$. I tried this by developing the $L$ of Table XVIII. by Cauchy's process as a function of $c$ and $z$,* and thus ascer-

---

* This formula is—

$$L = \log^{-1}(3{\cdot}13245)\begin{array}{l} \times\{1 - c\times L^{-1}(8{\cdot}55692) + c^{2}\times L^{-1}(7{\cdot}07878) - c^{3}\times L^{-1}(5{\cdot}15437)\} \\ \times\{1-(3+z)^{2}\times L^{-1}(8{\cdot}14374)+(3+z)^{2}+L^{-1}(6{\cdot}99018)-(3+z)^{3}\times L^{-1}(5{\cdot}91248)\}. \end{array}$$

The variable in the third factor is $3 + z$ instead of $z$, for a reason already assigned. The products of $c$ and $z$ were not used, the approximation being sufficient without them, as the ten observations of the Table are represented with a mean error of 1·59, and a maximum one of 2·91.

taining what increase of $c$ would produce $L - L'''$ in these three instances. For 115 it is 6·32; for 116, 6·29; but for 117 it is only 3·66. As, however, the last is not to be depended on, because it goes far beyond the largest $c$, on which the interpolation is founded, the close agreement of the other two seems to confirm the supposition. It must, however, be remarked that even the highest of these ratios will not entirely explain the excess of No. 113 over No. 112. It deserves to be noticed that the separation in these experiments always took place between the keeper and the discs, never between the discs and the magnet.

It was not within the scope which I proposed to myself to try the power of this magnet at sensible distances, but in a few instances I did so, interposing at the keeper plates of brass $0^{\mathrm{i}}{\cdot}12$ thick.

TABLE XXVI.

| | $h$. | Normal. | $T$. | $I = 0^{\mathrm{i}}{\cdot}12$. | $I = 0^{\mathrm{i}}{\cdot}24$. | $T$. | $\psi$. | Helices. | Observations. |
|---|---|---|---|---|---|---|---|---|---|
| 118 | 2·1 | 1088·73 | 77°·1 | 89·11 | . . . . | 77°·1 | 1058·77 | BB′ at keeper, . | 6, 6, 0 |
| 119 | 4·1 | 831·35 | 72 ·4 | 25·71 | 8·45 | . . . . | 552·55 | FF′ at keeper, . | 5, 1, 1 |
| 120 | 8·1 | 784·54 | 74 ·2 | 25·36 | 7·38 | . . . . | 548·06 | Ditto, . . . | 5, 1, 1 |
| 121 | 10·8 | 769·00 | 73 ·3 | 25·36 | 7·62 | . . . . | 551·26 | Ditto, . . . | 5, 1, 1 |
| 122 | 10·1 | 1001·49 | 73 ·1 | 243·27 | . . . . | 77°·6 | 2005·72 | FF′, BB′, JJ′, KK′, LL′, . . | 12, 12, 0 |
| 123 | 10·1 | 698·25 | 70 ·3 | 67·39 | . . . . | 77°·6 | 1997·47 | Do., slide removed. | 12, 12, 0 |

The great diminution caused by these small intervals is remarkable, especially where the helices are close to the keeper, and part of the cylinders is uncovered; the force then being only the 29th part of its ordinary amount. In No. 122, where the long cylinders are entirely covered with spires, it is much less considerable, the force being nearly one-fourth; and even the removal of the slide in the following one does not alter this fact, which is in accordance with the results of Table xv. It follows from this that in electro-magnetic machines, the magnet should be of considerable length, and covered uniformly with the spires. At the double distance $0^{\mathrm{i}}{\cdot}24$ the law of decrease is nearly the inverse square of the distance; the deviation from it being due to the distribution of the magnetism on the polar surfaces; but this is evidently not the law which prevails at the distances of normal contact.

I think it follows from what I have stated that there is little probability of making any progress in the investigation of the law of inductive transmission of magnetism, till that of the composition of magnetic forces has been developed. In the hope of giving some additional data which may aid in this, I add results obtained with some magnets differing in construction and dimensions from that which has been examined in such detail,—three of which have already been noticed in Table xx.

The first of these is that which I use for ordinary experiments; its cylinders are $3^{i}$ diameter and $12^{i}$ long, their centres $6^{i}$ apart; their base $3^{i}$ by $2^{i}\cdot5$. The helices are lapped with copper wire No. 12, and contain 1070 spires.* The keeper which I first used was $2^{i}\cdot5$ high by $2^{i}$ broad; therefore, only 0·71 of the section of the cylinder. With it I obtain—

### TABLE XXVII.

| | *L.* | *T.* | $\psi$. | Λ. | λ. | *L* with *I* = 0·12. | Observations. |
|---|---|---|---|---|---|---|---|
| 124 | 1503·97 | 69°·34 | 1678·88 | . . . . . | . . . . | 334·90 | 6 |
| 125 | 1300·06 | 71 ·65 | 1213·26 | 189·08 | 6.96 | 187·85 | 12 |
| 126 | 1152·97 | 68 ·05 | 916·43 | 192·66 | 7·54 | 111·40 | 12 |
| 127 | 907·72 | 66 ·20 | 617·00 | 194·43 | 6·66 | 50·81 | 12 |
| 128 | 569·14 | 66 ·7 | 309·54 | 148·34 | 6·04 | 11·79 | 12 |

I suspected that the keeper was too small, from the intense display of free magnetism; and, therefore, two pieces of iron, half an inch thick, and $2^{i}\cdot5$ high, were carefully fitted to the sides of the keeper and face of the magnet, and screwed firmly to the former while the magnet was powerfully excited; they now make the keeper 1·06 of the area of the cylinder. This addition gives a considerable increase of force, as might be anticipated from the principles explained in (*a*) and (*c*). I did not, however, expect to find so great a difference; as it is stated that a magnet lifts more powerfully when the keeper is slightly rounded, so as to touch in a small surface.

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* It is a singular fact that though the wire was purchased at the same time and place, the resistances of the two equal lengths were found to be 58·187 and 44·836 of my units, without any sensible difference of quality. This anomaly has since been fully investigated by Dr. W. THOMSON.

TABLE XXVIII.

| | $L$. | $T$. | $\psi$. | $\Lambda$. | $\lambda$. | $L$ with $I=0\cdot12$. | $L$ at 60. | Observations. |
|---|---|---|---|---|---|---|---|---|
| 129 | 1666·53 | 70°·5 | 1685·02 | 251·55 | 6·66 | 361·44 | 1698·40 | 12 |
| 130 | 1467·61 | 72°·0 | 1200·78 | 253·24 | 6·96 | 241·56 | 1498·93 | 12 |
| 131 | 1286·97 | 70°·6 | 915·91 | 253·24 | 8·75 | 130·31 | 1311·72 | 12 |
| 132 | 1066·87 | 68°·7 | 612·69 | 244·97 | 7·16 | 60·63 | 1073·25 | 12 |
| 133 | 667·80 | 67°·7 | 310·17 | 216·50 | 4·76 | 13·88 | 670·64 | 11 |

The thermometer correction has not been specially investigated, but I use that for the 2-inch magnet, with cylinders of $10^{\mathrm{i}}\cdot1$, as the greater diameter will compensate the greater length. The two sets of $L$ are in a mean ratio of 1·135, decreasing a little from the lower to the higher. As this is of the same circuit as the hollow magnet of my first Paper, their actions can be compared with theory very easily, by Tables I. and II. Since A in equation (4) is as $r^2$, it is obvious that if in two different magnets the radius of the magnet bears the same ratio $\rho$ to that of the spire, the series expressing the action of the latter on the former must have the same value in each case. Therefore, it is only necessary to enter these Tables with $b=\frac{b'}{r'}$, and multiply the result by $r'$. I thus find that the ratio of these two should be 3·139. Comparing them, however, by interpolating for the $\psi$ of the large one from the Table of the other, I get the ratios—

| | |
|---|---|
| 129, | 2·66. |
| 130, | 2·54. |
| 131, | 2·36. |
| 132, | 2·14. |
| 133, | 1·82. |

This seems to indicate that the central portion of the large magnet is either inactive, or perhaps even in an opposite polar condition to the exterior part.*

The residual excitation $\Lambda$ (that which remains when the current is withdrawn before the keeper is raised) is constant for a $\psi$ of 916 and upwards, decreasing below this in accordance with my former observations, which led me to conclude that this occurs for a certain $\psi$ which I call $B$, possessing some notable properties.* The residual magnetism, or, as M. Joule terms it, the "Set of the Magnet," is always what is left by a single excitement; for in each of these experiments the polarity was reversed: its amount in respect of the total $L$ is insignificant. The force when the brass plates are interposed is of considerable amount with this magnet for its higher powers, and follows a very different law from that which prevails in actual contact, being as $\psi^2$. This, as is obvious, implies that the magnetism excited *when the poles are not connected* is simply as $\psi$,—a fact which apparently depends on its comparatively small intensity.

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* It is probable that the entire of the 2-inch solid magnets is effective, at least with high exci-

As I wished to ascertain the properties of an electro-magnet composed altogether, or in part, of hard steel, one was prepared, and another exactly similar was made of iron to serve as a point of comparison. As I doubted the possibility of hardening uniformly masses of steel as large as those of either of the magnets already described, these were made of smaller dimensions, the cylinders $1^{i}$ diameter and $7^{i}{\cdot}85$ long, solid except that they have at the top holes 0·25 diameter and 0·5 deep, to receive thermometers. The base and keeper are $1^{i}$ high by $1^{i}{\cdot}5$ broad, and the distance of the centres is $6^{i}$. As the steel cylinders fit the base and

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tation. Comparing the power of the hollow $5\frac{1}{2}$-inch magnet (II. p. 512) with one of $2^{i}$ solid, and the same length (given II. p. 520, No. 62), I find—

| | |
|---|---|
| Observed powers as, . . . . | 10·65 : 4. |
| Theoretic, . . . . . . . . | 10·43 : 4. |
| Section, . . . . . . . . . | 10·00 : 4. |

The hollow 2-inch gives, compared to a solid one of the same diameter and length (I. p. 295, Note),

| | |
|---|---|
| Observed powers as, . . . . | 3·03 : 4. |
| Theoretic, . . . . . . . . | 3·18 : 4. |
| Section, . . . . . . . . . | 3·00 : 4. |

And the solid inch compared with the above No. 62—

| | |
|---|---|
| Observed powers as, . . . . | 1·09 : 4. |
| Theoretic, . . . . . . . . | 1·22 : 4. |
| Section, . . . . . . . . . | 1·00 : 4. |

As in the hollow magnets the iron is only $0^{i}{\cdot}5$ thick, we may suppose it is all uniformly magnetized; and the agreement shows that the other must be so too.

* When the keeper is separated from the poles by discs of paper $0^{i}{\cdot}0041$ thick, $\Lambda = 111{\cdot}44$ with $\psi = 900$. With the interval 0·12 there is no sensible value of it.

keeper of the iron magnet, I could have one all iron, one in which the parts excited are steel, but the induced parts iron, and one all steel. The helices N, N′ first prepared are rolled on wooden bobbins $1^{i}{\cdot}33$ diameter and $7^{i}$ long, containing 630·4 spires in four layers, with an external diameter $1^{i}{\cdot}95$. Afterwards, for temperature experiments, helices O, O′ were rolled on copper bobbins, $2^{i}{\cdot}8$ diameter by $5^{i}{\cdot}7$ long, with eight layers of No. 12, external diameter = 4·66, containing 677 spires. When used, they were blocked up to be in contact with the keeper, and, in consequence of the average distance of their spires from the poles being less, they are more effective than N, N′, in the ratio of 1 : 0·96;* they are less resisting, their measures being 59·840, and 78·416. They were generally used, but for the higher $\psi$s the others were added collaterally, and the $\psi$ computed by the method given in my second paper, p. 524.

*Small Iron Magnet.*—It was necessary to begin with the temperature correction, for I had now learned that this depends on the size as well as the form of the magnet. Two copper cylinders, with central tubes which fit on the arms, are connected below by a cross tube which is coupled to a small steam boiler, and are provided with means of escape for the waste steam and condensed water: on these the helices O, O′ were placed, and the $\psi$ was made 600. In the first of the following Table the magnet was cooled 27° below the temperature of the room, by keeping a stream of ice-cold water flowing through the cylinders.

Table XXIX.

| | *L.* | *T.* | *O − C.* | Observations. |
|---|---|---|---|---|
| 134 | 213·69 | 38°·2 | + 0·08 | 6 |
| 135 | 211·96 | 69 ·3 | − 0·09 | 6 |
| 136 | 210·79 | 83 ·5 | − 0·72 | 6 |
| 137 | 212·17 | 92 ·5 | + 0·85 | 6 |
| 138 | 212·09 | 104 ·3 | + 1·10 | 6 |
| 139 | 209·56 | 115 ·5 | − 1·10 | 6 |
| 140 | 208·77 | 138 ·0 | − 1·14 | 6 |
| 141 | 208·51 | 155 ·7 | − 0·54 | 6 |
| 142 | 210·20 | 163 ·3 | + 1·63 | 6 |
| 143 | 208·43 | 181 ·4 | + 1·27 | 6 |
| 144 | 205·19 | 188 ·9 | − 1·23 | 6 |

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* Determined by thirty observations.

From these is deduced by CAUCHY'S interpolation—

$$L=212{\cdot}43\,\{1-t\times L^{-1}(6{\cdot}31639)+t^{2}\times L^{-1}(4{\cdot}28451)-t^{3}\times L^{-1}(2{\cdot}19549)\},$$

in which $t=T-60$. The fourth column shows the excess of the observed above the calculated value. The coefficients differ widely from those for a 2–inch magnet of the same length, for which the logarithms would be—

7·23121; 5·33385; 2·92184.

A series was then taken of the $L$ corresponding to various values of $\psi$. For the three highest, N, N′ were used collaterally with O, O′.

TABLE XXX.

| No. | $L$ at 60°. | $T$. | $\psi$. | $\frac{\Delta L}{\Delta\psi}$. | A. | λ. | Observations. |
|---|---|---|---|---|---|---|---|
| 145 | 265·89 | 82°·2 | 2591·67 | 0·02145 | 61·35 | . . | 6 |
| 146 | 254·29 | 80 ·3 | 2050·88 | 0·00963 | 56·07 | . . | 6 |
| 147 | 249·93 | 81 ·2 | 1598·20 | 0·02750 | 65·02 | . . | 6 |
| 148 | 238·97 | 67 ·7 | 1200·61 | 0·04179 | . . . | . . | 6 |
| 149 | 230·69 | 71 ·3 | 1002·03 | 0·02780 | . . . | 2·40 | 6 |
| 150 | 225·12 | 66 ·6 | 801·66 | 0·07580 | 65·21 | . . | 6 |
| 151 | 212·80 | 70 ·7 | 601·70 | 0·10399 | 61·33 | 1·99 | 6 |
| 152 | 191·89 | 68 ·4 | 400·62 | 0·10622 | . . . | . . | 6 |
| 153 | 175·29 | 69 ·1 | 300·75 | 0·35154 | . . . | . . | 6 |
| 154 | 139·95 | 67 ·8 | 200·22 | 0·75840 | 43·25 | . . | 6 |
| 155 | 63·89 | 68 ·0 | 99·93 | | . . . | 1·75 | 6 |

The ratio of this magnet to the 2-inch one may be derived from No. 65 in Table XIII. In that the arms are $8^{i}{\cdot}1$, nearly the same as here, and the efficiency of the helices is not very different, their diameters being $2^{i}{\cdot}26$ and $3^{i}{\cdot}93$. The $\psi$ is 547·65, which I find, by interpolation, would give with the small magnet 207·94. The actual $L=765{\cdot}12$; so, with four times the section, it is

3·68 times as powerful. By theory the ratio should be 3·27 : 1. There is the same decrease in $\frac{\Delta L}{\Delta \psi}$ as $\psi$ increases, which was remarked in the other magnets, and from which the existence of a limit to $L$ was inferred.

In this magnet (as in the others), $\Lambda$ is constant for every value of $\psi$ above one which is less than 600. At 200 it has considerably decreased, so that the critical value is probably near 300. Few observations of $\lambda$ were taken, but those few seem in due proportion to the other magnets.

The iron cylinders were then removed, and those of steel substituted. These were tempered to a pale straw colour, and their polar surfaces, which *cast* in this process, were made true by careful working with a tool made of lac fused with fine corundum. The same helices were used, but as it was desirable that the permanent magnetism $\lambda$ should not be disturbed, the current was not reversed in each observation of a set. The temperature correction was first sought with $\psi = 1282\cdot92$.

TABLE XXXI.

| No. | $L$. | $T$. | $O-C$. | $\Lambda$. | $\lambda$. | Observations. |
|---|---|---|---|---|---|---|
| 156 | 135·84 | 49°·0 | + 1·59 | . . . | . . . | 5 |
| 157 | 134·41 | 67 ·7 | − 0·66 | . . . | . . . | 7 |
| 158 | 135·02 | 81 ·8 | − 0·62 | . . . | 11·75 | 4 |
| 159 | 135·52 | 96 ·5 | − 0·67 | . . . | . . . | 5 |
| 160 | 136·95 | 107 ·2 | + 0·38 | . . . | . . . | 5 |
| 161 | 137·79 | 121 ·7 | + 0·77 | . . . | . . . | 6 |
| 162 | 137·40 | 130 ·5 | − 0·12 | . . . | . . . | 5 |
| 163 | 138·43 | 146 ·4 | + 0·72 | . . . | . . . | 5 |
| 164 | 137·29 | 159 ·2 | − 0·71 | 45·86 | 12·68 | 6 |
| 165 | 137·93 | 172 ·9 | − 0·36 | . . . | . . . | 9 |
| 166 | 138·02 | 186 ·6 | − 0·51 | 43·43 | 11·75 | 6 |

These give

$$L = 134\cdot74\{1 + t \times L^{-1}(6\cdot51193) - t^2 \times L^{-1}(3\cdot91068)\}.$$

I did not anticipate the remarkable difference between this correction and that of the iron magnet, especially as heat is known to lessen the power of a permanent magnet. As far as the base and keeper are concerned, there can be no difference; their action must tend to make it negative, and therefore the change may be referred to a diminution of coercive force, which permits a greater development of magnetism. The correction is, therefore, the difference of two opposite actions. The formula gives $L$ a maximum at 199°·7, and, if it could be depended on so far beyond the observations on which it rests, indicates that the correction would become negative at 468.

The following are the results by varying $\psi$, the negative sign before it denoting that the current is reversed; and that before $L$, that the polarity is changed:—

TABLE XXXII.

| No. | $L$ at 60°. | $T$. | $\psi$. | $\frac{\Delta L}{\Delta \psi}$. | λ. | Observations. |
|---|---|---|---|---|---|---|
| 167 | 202·56 | 113°·3 | 2910·72 | | 10·71 | 5 |
| | | | | 0·04467 | | |
| 168 | 170·27 | 100 ·8 | 2187·84 | | 10·82 | 5 |
| | | | | 0·03560 | | |
| 169 | 133·37 | 85 ·5 | 1151·35 | | 12·17 | 5 |
| | | | | 0·05976 | | |
| 170 | 125·18 | 78 ·3 | 1014·31 | | 12·62 | 5 |
| | | | | 0·10475 | | |
| 171 | 108·90 | 84 ·9 | 858·90 | | 12·09 | 5 |
| | | | | 0·06256 | | |
| 172 | 101·63 | 70 ·9 | 742·70 | | 12·62 | 5 |
| | | | | 0·12286 | | |
| 173 | 80·62 | 80 ·3 | 571·69 | | 12·00 | 5 |
| | | | | 0·12942 | | |
| 174 | 68·58 | 75 ·8 | 478·66 | | 11·91 | 5 |
| | | | | 0·12671 | | |
| 175 | 55·53 | 65 ·2 | 375·67 | | 12·09 | 5 |
| | | | | 0·11433 | | |
| 176 | 50·79 | 67 ·4 | 334·21 | | 11·89 | 5 |
| 177 | 46·82 | 68 ·2 | 331·79 | 0·13153 | 8·34 | 5 |
| 178 | 44·52 | 68 ·0 | 286·54 | | 11·69 | 5 |
| 179 | 42·46 | 67 ·3 | 287·24 | 0·14736 | 9·65 | 5 |
| 180 | 31·18 | 67 ·8 | 195·91 | | 11·49 | 5 |
| 181 | 26·40 | 65 ·2 | 201·10 | 0·13777 | 8·64 | 5 |
| 182 | 17·74 | 67 ·4 | 98·36 | | 11·29 | 5 |
| | | | | 0·06185 | | |

TABLE XXXII—*continued.*

| No. | $L$ at 60°. | $T$. | $\psi$. | $\frac{\Delta L}{\Delta \psi}$. | $\lambda$. | Observations. |
|---|---|---|---|---|---|---|
| 183 | 11·78 | . . . | 0·00 | | 11·46 | 20 |
| | | | | 0·02844 | | |
| 184 | 9·04 | 67·0 | − 98·33 | | 5·72 | 5 |
| | | | | 0·06366 | | |
| 185 | 2·48 | 65·0 | −201·38 | | 5·72 | 5 |
| | | | | 0·00836 | | |
| 186 | 1·76 | 66·4 | −287·49 | | 4·45 | 5 |
| | | | | 0·09299 | | |
| 187 | − 2·35 | 66·7 | −331·69 | | −0·54 | 5 |
| | | | | 0·16350 | | |
| 188 | − 9·83 | 69·7 | −377·44 | | −0·85 | 5 |
| | | | | 0·24729 | | |
| 189 | −35·66 | 71·2 | −481·65 | | −3·85 | 5 |

Here the first point to be noted is the inferior magnetism as compared to that which the same $\psi$ would excite in iron. The inferiority is, however, chiefly in the lower numbers. Thus, for $\psi = 200$, the two $L$'s are as 1 : 5·6 ; at 2600 as 1 : 1·2. This shows that they would ultimately become equal, and that the difference arises not from steel being less capable of magnetism, but from its greater coercive force requiring a higher $\psi$ to bring it out. This follows still more plainly from the values of $\frac{\Delta L}{\Delta \psi}$, which above 600 actually exceed those of iron, in accordance with the inference which I made from the phenomena of $\Lambda$, that the coercive force increases more slowly than the magnetism.

With this magnet $\Lambda$ was not observed ; for in 1851, when these experiments were made, I was not aware of its importance.

The series of $\lambda$ is complete ; this is the permanent magnetism which remains after the current is stopped, and after the keeper has been raised from *both cylinders.*[*] As might be expected, it is much greater than in iron, and it requires a certain continuance of excitation to produce its full amount, for when ithas been in part destroyed, it is not restored entirely, even by a set of five in which $L$ is four or five times its maximum. The three bracketed pairs are examples of this.* The relations to $L$ deserve attention: from $\psi = 742$ to $\psi = 98$, $\frac{\Delta L}{\Delta \psi}$ is nearly constant, but below this a new order of dependence arises, in which $\lambda$ enters. Thus $\psi = 98$ adds only 5·96 to $\lambda = 11{\cdot}78$; if the current be reversed, instead of reversing the polarity and giving $-17{\cdot}74$ (the sign $-$ when applied to $L$ meaning that what had been a north pole is now a south), $L$ continues positive $= + 9{\cdot}04$, 2·74 less than $\lambda$; and when the reverse current is withdrawn, it is found that no permanent change in the condition of the magnet has been made, for $\lambda$ is unaltered. With $\psi = 196$, $L$ is 31·18, a much greater proportional increase; with $-\psi = 201$ it is still positive, $= + 2{\cdot}48$, but the molecular state has been permanently altered, for $\lambda$ is only 5·72, and the reapplication of $\psi = + 201$ does not raise it above 8·64 with an $L = 26{\cdot}40$. The same happens with the ± applications of $\psi = 287$ and 331, except that with the last $L$ becomes negative, while $\lambda$ retains the small positive value $+ 0{\cdot}54$. The two negative values, $-377$ and $-482$, give $\lambda$ negative, though far less than the values obtained by the same when positive, and the latter at once reproduces the full positive $\lambda$. I regret that I did not ascertain what negative $\psi$ would be required to give $\lambda$ its full negative value. All this confirms the inferences which I formerly made from the observations with the hollow magnet, that $L$ is a function both of $\psi$ and $\lambda$.

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[*] If raised only from one of them, the keeper remains in the state $\Lambda$, and of course is much more magnetic than in $\lambda$. This may give twice as great a value for $\lambda$ as the true one.

The iron parts of the magnet were then removed, and the steel keeper and base substituted. This alters the conditions, not merely because their induction is less than that of the iron ones, but also because they too become permanent magnets, and add the effect of this to that of the cylinders. In the first instance the temperature correction was sought, $\psi = 1282{\cdot}92$.

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* The brackets in the column of $\psi$ connect those which were used in computing $\frac{\Delta L}{\Delta \psi}$. Those were selected in which $\lambda$ might be supposed to retain its normal value, as in them only the molecular condition of the steel can be considered definite.

TABLE XXXIII.

| | *L.* | *T.* | *O – C.* | Observations. |
|---|---|---|---|---|
| 190 | 101·63 | 49°·6 | +0·21 | 5 |
| 191 | 108·61 | 67·6 | +3·43 | 6 |
| 192 | 107·60 | 83·4 | +0·03 | 4 |
| 193 | 107·69 | 95·8 | +0·31 | 4 |
| 194 | 107·67 | 104·3 | −0·17 | 5 |
| 195 | 107·36 | 113·6 | −0·96 | 5 |
| 196 | 107·09 | 120·1 | −1·57 | 8 |
| 197 | 109·39 | 127·5 | +0·32 | 4 |
| 198 | 110·74 | 147·8 | +0·23 | 4 |
| 199 | 112·54 | 153·4 | +1·50 | 5 |
| 200 | 113·45 | 168·2 | +0·66 | 4 |
| 201 | 113·19 | 185·8 | −2·62 | 5 |

which give—

$$L = 104{\cdot}30\,\{1 + t \times L^{-1}\,(7{\cdot}08061) - t^2 \times L^{-1}\,(5{\cdot}14056) + t^3 \times L^{-1}\,(2{\cdot}95041)\}.$$

The contrast between this result and the two preceding is great. With the iron magnet the change produced by the extreme range of temperature is a decrease from 214 to 205. When three-sevenths of the circuit are iron, and the rest steel, it is an increase from 135 to 138; and when all is steel, from 102 to 113. The difference is more evident on computing the *proportional* change from 60° to 190°. It is for—

| | |
|---|---|
| Iron | − 0·02886. |
| Compound | + 0·02849. |
| Steel | + 0·11892. |

In the two last, the parts subject to direct excitation are the same; in the two first they differ; on the other hand, the last differ in the parts which act solely by induction, while the first agree. Hence it seems probable that both in direct and inductive magnetization, the action of heat on steel is the reverse of iron.

A series for various values of $\psi$ is given in—

## TABLE XXXIV.

| | $L$ at 60. | $T$. | $\psi$. | $\frac{\Delta L}{\Delta\psi}$ | A. | λ. | Observations. |
|---|---|---|---|---|---|---|---|
| 202 | 158·35 | 89°·7 | 2961·28 | 0·02362 | | | 5 |
| 203 | 146·87 | 94 ·8 | 2475·26 | 0·02198 | 55·27 | 20·89 | 5 |
| 204 | 138·97 | 73 ·0 | 2115·78 | 0·05045 | 53·48 | 16·49 | 5 |
| 205 | 84·95 | 65 ·9 | 1044·96 | 0.07225 | 44·40 | 15·16 | 5 |
| 206 | 44·87 | 66 ·1 | 490·25 | 0·06141 | | 13·55 | 5 |
| 207 | 38·73 | 67 ·7 | 390·27 | 0·06511 | 26·96 | 14·42 | 5 |
| 208 | 32·77 | 64 ·9 | 298·73 | 0·07422 | | 13·55 | 5 |
| 209 | 25·09 | 63 ·6 | 195·25 | 0·04937 | | 14·42 | 5 |
| 210 | 15·45 | | 0·00 | 0·02371 | | | 14 |
| 211 | 10·82 | 63 ·1 | − 195·25 | 0·03769 | | | 5 |
| 212 | 6·92 | 63 ·8 | − 298·73 | 0·03376 | 9·06 | 9·04 | 5 |
| 213 | 3·42 | 67 ·1 | − 390·97 | 0·06291 | | 6·04 | 5 |
| 214 | − 2·87 | 65 ·5 | − 490·25 | 0·12306 | | − 1·29 | 5 |
| 215 | − 71·13 | 68 ·8 | − 1044·96 | | | − 10·71 | 5 |

For the same $\psi$, $L$ is less than even in Table XXXII., the inferior inductive transmission of the keeper and base lowering the excitation of the cylinders. The fifth column shows that the average change of $L$ for a given change of $\psi$ is less, but that it is more uniform, being in fact almost constant within the range of the positive values. It is probable that for the three magnets, the maximum $L$ is about 300; now with the iron one $\psi = 2592$ gives $\frac{9}{10}$ of this; with the compound 2960 gives $\frac{2}{3}$ of it, and with the steel 2961 gives $\frac{8}{15}$. With a reversed current $L$ continues positive much longer than in the preceding case, as might be expected from the permanent magnetism of the keeper and base opposing the action of the current on the cylinders. In No. 212 the upper half of what in ordinary cases is the N cylinder was S, the lower N, and *vice versâ* in the other cylinder; the polarities of the keeper remaining unchanged, but the natural distribution was restored when the current ceased.

The values of $\Lambda$ are greater than those corresponding to the same $L$ in the iron magnet, and their maximum would probably be higher, but their increase with $\psi$ shows that it was not reached, though No. 202 would probably have given it.

$\lambda$ is, of course, still greater than in the compound magnet, bearing a considerable proportion to the whole force. In the two the lengths of saturated steel are as 7 : 4; the $\lambda$s as 7 : 5·3, the excess in the latter being due to the iron keeper. I have already remarked that when the steel has been fully magnetized in one direction, that tendency continues, so that even after several reversions of its polarity, it is far more easily magnetized in the original direction than the other. Analogous to this is the fact, which is shown still more clearly than in Table XXXII., that a positive $\psi$ gives a larger $L$ than a negative; and that the latter, unless it be great, merely destroys a portion of $\lambda$, the $L$ being scarcely different from what is left of that. Thus in Nos. 208, 212, the positive $\psi$ gives $32{\cdot}77 = \lambda + 17{\cdot}32$; therefore, on any supposition of the resolution of magnetic force, we should expect its effect, when negative, to overpower $\lambda$, and give a negative result; we, however, find $L = +6{\cdot}92$ and $\lambda = 9{\cdot}04$, with the additional fact that under such circumstances the state $\Lambda$ has no existence. In 207, 213, + 390 gives 38·7, and 14·4; − 390 gives + 3·4, and 6·0: the next pair give, the positive 44·9, and 13·6; the negative − 2·9, and − 1·3. It seems from this, that steel (and, though in a less degree, iron) undergoes by being fully magnetized some change, which continues when the magnetism is destroyed. In virtue of that change it resists an opposite excitation, which may lessen its existing polarity, or even produce an opposite one; but the bias remains until an overwhelming power is applied which is sufficient to destroy it altogether, and substitute an opposite one in its stead. This, however, must far surpass that which originally produced it. In the present instance even the high $\psi$ 1045 falls far short of this; and I think it not improbable that, had the magnet been left to itself, these $\lambda$s, which were diminished by reversed excitation, would have returned to their original magnitudes.

In examining the different series of $L$ given by the various magnets with which I have experimented, it will be observed that $\frac{\Delta L}{\Delta \psi}$, the rate of increase of $L$ for a given change of $\psi$ decreases as this variable increases, and so as to indicate that in each of them $L$ has a limit which it cannot pass by any amount of excitation. When I first noticed this, I explained it by supposing that the cause of magnetism, whatever it be, is present in each molecule only in finite quantity: if it be a hypothetic fluid decomposed into two of opposite powers, when all of it is so resolved, the process must stop. If we assume Ampère's currents, when all of them are forced into the same plane and direction, there can be no further development of magnetism. This still seems to me to be the case, with a slight modification, which makes the limit depend also on the length of the circuit; for as we must consider the force at each pole to be the resultant of those which I have described as M and M′; and as each of these is the resultant of two others transmitted by induction, it follows that even an infinite $\psi$ would not produce the *total* magnetization of the polar surfaces, as long as the portions of the circuit through which this induction takes place have a *finite* magnitude. The hollow magnet which I first used, and which with $\psi = 4639{\cdot}27$ gave $L = 769{\cdot}75$, could not have passed 800 with any $\psi$, to judge from the curve of those variables. Had this magnet been solid, the limit might be expected to be one-third higher, or $= 1067$; but in the solid 2-inch magnet, with a circuit reduced to $16^{i}{\cdot}2$ instead of $36^{i}$, it is seen from Table XII. that this is exceeded by a $\psi$ not a fourth of the above, and with a $\psi = 2548{\cdot}59$ I got on one occasion $L = 1379{\cdot}11$. With the small iron magnet the maximum is about 300, its section being one-third, and its circuit about three-fourths of those of the hollow one. These facts show that the limit is determined not merely by the section of a magnet, but by the other causes which I have pointed out as influencing the efficiency of the helices. More precise information cannot be expected till we possess an exact theory of the electro-magnet, but I may be permitted to give here an empirical formula which represents a considerable portion of these experiments with sufficient precision.

It was suggested by examining the march of the sets of $\frac{\Delta L}{\Delta \psi}$. If $L$ were as $\psi$, $\frac{dL}{L}$ would be as $\frac{d\psi}{\psi}$; but it is not so, and the second must be multiplied by a factor decreasing as $L$ or $\psi$ increases. Admitting a limit of $L = A$, the most obvious form of this factor is $A - L$, which would give—

$$\frac{dL}{L \times (A - L)} = \frac{d\psi}{b\psi};$$

integrating which—

$$\frac{L}{A - L} = K \times \psi^{\frac{A}{b}}.$$

Trying this by the numbers of Table XII., I found for $\frac{A}{b}$ 0·9918, so near unity that $b$ may be taken $= A$, and the equation becomes finally—

$$L = \frac{A \times \psi}{B + \psi}. \tag{18}$$

$B$ being the $\psi$ which will give half $A$, a quantity which, as I formerly remarked, seems to have some marked properties, among which are that $\Lambda$ is constant for every $\psi$ which is greater than it, and that for all below it the $L$ is not the same for direct and reverse currents if there be any permanent magnetism. The formula supposes $L$ to vanish with $\psi$; and, therefore, only applies to the higher portion of the series. Perhaps it may be a residual portion of the true formula; but at all events it represents so much, that its constants appear to have a real physical significance, and I therefore give them in—

TABLE XXXV.

| Magnet | Sect. | *c.* | *A.* | *B.* | P. Error. |
|---|---|---|---|---|---|
| Small Iron, Table XXX., . | 1 | 27·7 | 277·87 | 185·20 | ± 2·21 |
| Compound, Table XXXII. . | 1 | 27·7 | 331·52 | 1796·76 | ± 2·99 |
| Steel, . . Table XXXIV.. | 1 | 27·7 | 309·85 | 2719·19 | ± 1·85 |
| Hollow, . . . 0 . . | 3 | 36·0 | 781·07 | 356·07 | ± 10·61 |
| 2-Inch, . Table VIII., . | 4 | 12·3 | 2032·16 | 392·68 | ± 9·84 |
| Do. . Table XII., . | 4 | 16·2 | 1399·14 | 293·78 | ± 10·41 |
| Large, . . Table XXVIII., | 9 | 36·0 | 2569·40 | 867·40 | ± 9·42 |

Of these the first represents the first 10 of Table XXX., No. 155 being omitted, because in it the excitement appears to have been too weak to bring out the magnetism, as may be inferred from its being *less than half* No. 154. The same may be observed in Table VIII., No. 45, for which magnet I had a remarkable proof of it, trying the effect of a single pair of spires with $\psi=13\cdot56$: $L$ was only 12·97, only 0·071 of No. 45, while the $\psi$ is 0·272. In the second and third all are represented in which $\psi$ is positive. In the fourth the highest 16 of the Table were taken: the agreement here is the worst, caused by the aberrance of the highest one, which is very discordant, owing to the magnet having been, for some time before it was taken, only slightly excited. In such cases I have always found a great excess. The fifth is probably too far from the maximum, and the sixth would be much improved by omitting No. 58, which is not sufficiently excited.

From the fragmentary character of this Paper, and those which preceded it, it may be useful to conclude with a brief summary of the principal results which they contain.

An electro-magnet, whose circuit is closed, differs from one whose poles are not connected, in having little free magnetism, but a much higher polarization of its molecules.

In this condition the magnetism of each molecule is in equilibrium under the action of four antagonist forces:—

1. The direct action of the helices on each molecule.
2. The action of the other magnetized molecules transmitted by induction through the iron: these tend to keep the two polarities apart.
3. The coercive force, which in general seems to resist any magnetic change. And
4. The mutual attraction of the polarities,—oppose their separation.

If, when the magnet is thus excited, the current which passes through the helices be stopped, the force 1 vanishes, 4 prevails over 2, which therefore decreases, but which is now assisted by 3 opposing the decrease, as it had done the increase of polarity, and a new magnetic equilibrium occurs, which continues until the keeper is raised, when almost the entire of the force 2 is destroyed. This "residual excitation," whose force I denote by $\Lambda$, is of a given amount as long as the previous excitation can produce a force greater than half the maximum power of the magnet; below that it decreases. It is not proportional to the maximum; and if a current be passed while the magnet is in this state, the effect produced is less than would be caused by adding it to another current capable of producing the force Λ. In this state all the molecules in the circuit must be equally polarized, for Λ is the same when only one arm has been excited. It occurs, though but feebly, even when the keeper is separated from the poles by a very small interval.

When the keeper is raised, and the force 2 is destroyed, a further decrease of the force takes place, till the coercive force 3 balances the attraction of the polarities. This is the case of residual or permanent magnetism, which I describe by the force λ; it is very powerful in hard steel, but is found in all iron however soft. By repeated excitation it rises to a maximum, and then is not entirely removed by reversing the current, unless that be able to produce half the maximum. If the magnet be hard steel, it is able to overpower a reverse excitation, whose $L$ would of itself considerably exceed it; and if destroyed it cannot be restored, but by one whose $L$ is four or five times its own amount.

An electro-magnet, like a permanent one, bears a greater load, if this be gradually increased.

It requires a considerable time to attain its full power, not less, in any of the magnets which I have used, than ten minutes.

It becomes less powerful by long-continued magnetization in one direction. This is connected with its acquiring permanent magnetism, and the reverse current then produces less effect than the direct, unless it can produce half the maximum. *That* current is, therefore, the best where the polarity is to reciprocate, as in electro-magnetic engines.

It is affected by a rise of temperature. If of soft iron, its power decreases, though irregularly, having minima and maxima between 32° and 220°. The coefficients of the interpolation formula which represent the change, vary with the diameter and length of the magnet.

In one of hard steel the power increases with the temperature from 50° to 190°; indeed, probably until the heat is sufficient to lower its temper. The amount of change is four times that of iron of the same dimensions.

In one whose keeper and base are iron, but the parts covered by the helices steel, there is an increase almost exactly equal to the decrease in the iron one.

The central part of the magnet is probably inactive.

The force at the pole of an electro-magnet is the resultant of four others transmitted to it by induction, two through the shorter distances between it and the centres of the helices, the other two through the complements of the circuit. When any of these distances is increased, the corresponding force diminishes. The effect of lengthening the entire circuit is considerably greater than that of lengthening the distance of the helices from the keeper.

The resultants of pairs of these forces can be obtained separately, but they cannot be further separated, as the law of this magnetic composition is not yet known.

The law of the inductive transmission of the magnetic force is equally unknown. It is not impeded by the magnetism of iron.

Whatever impedes this transmission lessens the power of the magnet.

The interposition of brass plates $0^{\mathrm{i}}\cdot12$ thick reduces it to a quantity varying from 0·24 to 0·03 of its normal amount, according to the nature of the magnet. In *this case* the force is as $\psi^2$, and, therefore, the development of magnetism as $\psi$.

Even the interval between the keeper and polar surfaces, though the contact be as close as possible, reduces it to 0·91, or 0·95.

Complete interruption of the circuit in the middle of the keeper reduces it to a value between 0·09 and 0·03, and one in the centre of the magnet from 0·70 to 0·18, the diminution being less as the circuit is longer, and the spires more uniformly distributed over it.

When both interruptions exist, the two halves of the magnet act as separate bar magnets; but in this case the power, when greatest, is only a thirtieth of the normal value.

A magnet, intended to act with the circuit closed, should have its spires collected as near the keeper as possible, and be as short as is compatible with having the necessary quantity of wire coiled on it; if it be designed to act at a distance, it should be of considerable length, and have the spires uniformly distributed over it.

If the resistance of one of the helices be greater than the internal resistance of the battery used, power is gained by employing them collaterally, but the expenditure of materials is doubled.

In magnets of the same length, but different diameters, the actions of similar spires are as these diameters.

The action of a helix, $\psi$, is represented by the quantity of current multiplied into the number of spires (not the length of wire, as is sometimes stated), and into a coefficient expressing the mean efficiency of these spires ; this efficiency decreases as the ratio of the spires' radius to that of the magnet increases, at first rapidly, but afterwards very slowly, for that portion of the magnet which is in its plane. On parts out of the plane the action may even increase with the distance, but it is much feebler than the other.

The lifting force $L$ is not proportional to any one power or exponential of $\psi$. The increase of it, corresponding to a given increase of $\psi$, lessens continually as $\psi$ increases. This diminution is least in hard steel, but only because that material requires a higher exciting force to develop its magnetism. The rate of this decrease shows that there must be a maximum $L$ for each magnet, which no magnitude of $\psi$ can make it exceed. This maximum is higher the greater the section of the magnet is, and the shorter its circuit. It seems the same for iron and hard steel.

When the excitation is very feeble, $L$ seems to depend on $\lambda$, the permanent magnetism, as well as on $\psi$ ; but in the higher powers solely on the latter. A tolerable approximation is given by an empirical formula,

$$L = \frac{\mathrm{A} \times \psi}{\mathrm{B} + \psi},$$

in which A is the maximum, and B that value of $\psi$ which would excite the magnet to half the maximum. This quantity appears to possess some remarkable properties, and may be considered a sort of modulus ; in steel, for instance, it is 14 times greater than in iron, and the fraction $\frac{\mathrm{A}}{\mathrm{B} \times \text{section}}$ appears to be a good measure of the efficiency of any magnet.